Radiation-hardness of VA1 with Sub-micron Process Technology

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Abstract— **We have studied the radiation hardness of the VA1, a Viking-architecture preamplifier VLSI chip. LSI samples are fabricated in 0.8 μm and 0.35 μm process technologies to improve the radiation hardness of the LSI for the Belle silicon vertex detector upgrade.**

We have observed significant improvement of the radiation hardness with 0.8 μm technology. Little degradation of noise and gain is observed up to a total dose of 20 Mrd for the VA1 fabricated in the 0.35 μm technology. We find that the radiation hardness improves with a scaling of better than t_{ox}^{-6} (t_{ox}: oxide thickness). Basic parameters of MOS FETs are also studied to understand the mechanism of radiation damage in the VA1.

I. Introduction

In the Belle B-factory experiment, the radiation dose in the silicon vertex detector (SVD)[1], [2] is found to be about 10 krd per month. The fractional noise increase of the original 1.2 μm CMOS VA1 chip used in the first Belle SVD was measured to be 1.6%/krd. This chip stopped functioning altogether above 200 krd. This level of radiation hardness is not adequate for long-term use in Belle.

It is thus crucial to improve the radiation hardness of the VA1 to 2 Mrd or more for 5 years of stable operation of an upgraded detector. We fabricated two iterations of the VA1 with sub-micron process technologies to achieve this goal.

II. Radiation Effects on MOS Devices

Radiation damage to a MOS FET is mainly caused by ionization charges trapped near or in the interface between the SiO_2 and the Si bulk[7]. Increased oxide trapping (fixed charge in the oxide layer) and interface trapping (localized electronic state very near the Si-SiO_2 interface) cause increased $1/f$ noise, mobility degradation (which then degrades transconductance and increases white noise) and threshold voltage shifts. The $1/f$ noise is caused by fluctuations of the number of carriers due to the trapping and detrapping of carriers by near-interface oxide traps. Thus the increase of $1/f$ noise is linearly proportional to the number of increased oxide traps. The mobility degradation is caused by the interaction between interface traps and carriers in the surface channel of MOS FETs, which decreases transconductance and increases white noise of the FET. Since oxide traps are positively charged, they produce negative threshold voltage shifts of MOS FETs. Interface traps produce positive threshold voltage shifts for n-channel MOS FETs and negative threshold voltage shifts for p-channel MOS FETs, because interface traps are negatively charged at n-channel threshold and are positively charged at p-channel threshold, depending on the position of the Fermi level.

It is well known that the intrinsic radiation hardness of CMOS ICs depends on the gate-oxide thickness, since a thinner oxide provides fewer ionization charges. In addition, trapped charges can escape via a tunneling effect. The threshold voltage shift in a MOS transistor will scale like the square of the gate oxide thickness (t_{ox}), which in turn is (approximately) proportional to the feature size of the process being used. Furthermore, it is known that the radiation hardness scales much better than t_{ox}^{-2} in the deep sub-micron region[8].

III. Test Samples

We fabricated the VA1 in the AMS 0.8 μm and 0.35 μm process technologies to improve radiation hardness. Table I shows the oxide thickness of a MOS FET in each process technology. A 1.2 μm process technology is used for the original VA1 chip.

TABLE I
Thickness of gate oxide for each process used for the samples.

feature size (μm)	1.2	0.8	0.35
oxide thickness (nm)	25	16	7.5

In this study, we also measure basic parameters (threshold voltage shifts, transconductance, increases in the number of oxide traps and interface traps) for MOS FET samples fabricated in the AMS 1.2 μm process as a function of radiation dose, in order to understand the radiation damage in the VA1.

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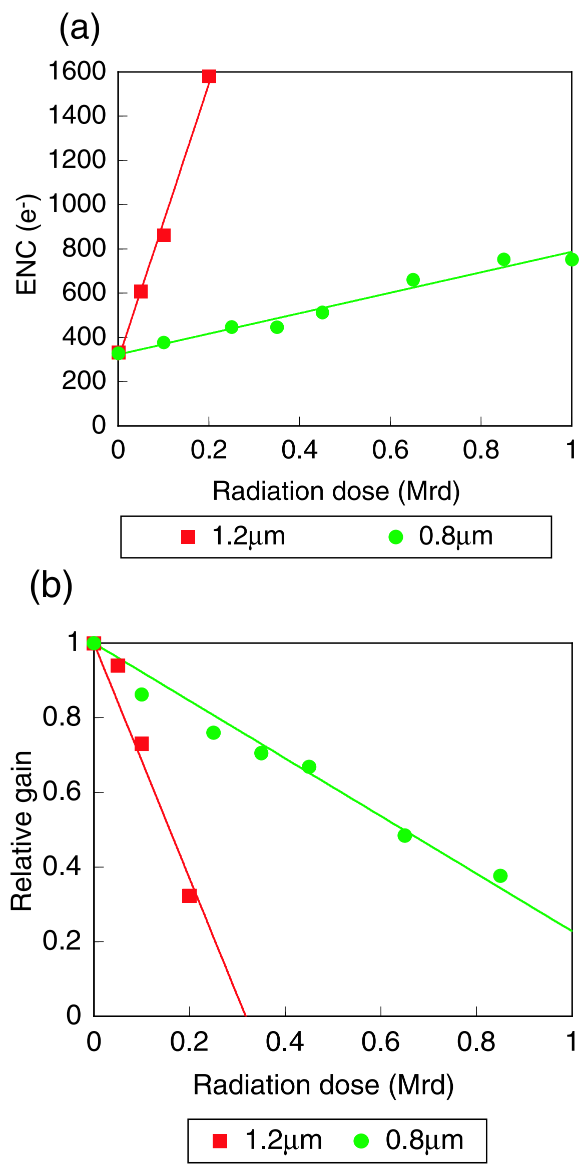

Fig. 1. Measured noise (a) and gain (b) of the 0.8 μm VA1 with 20 pF of load capacitance as a function of the total radiation dose. The results with 1.2 μm VA1 are also shown for comparison.

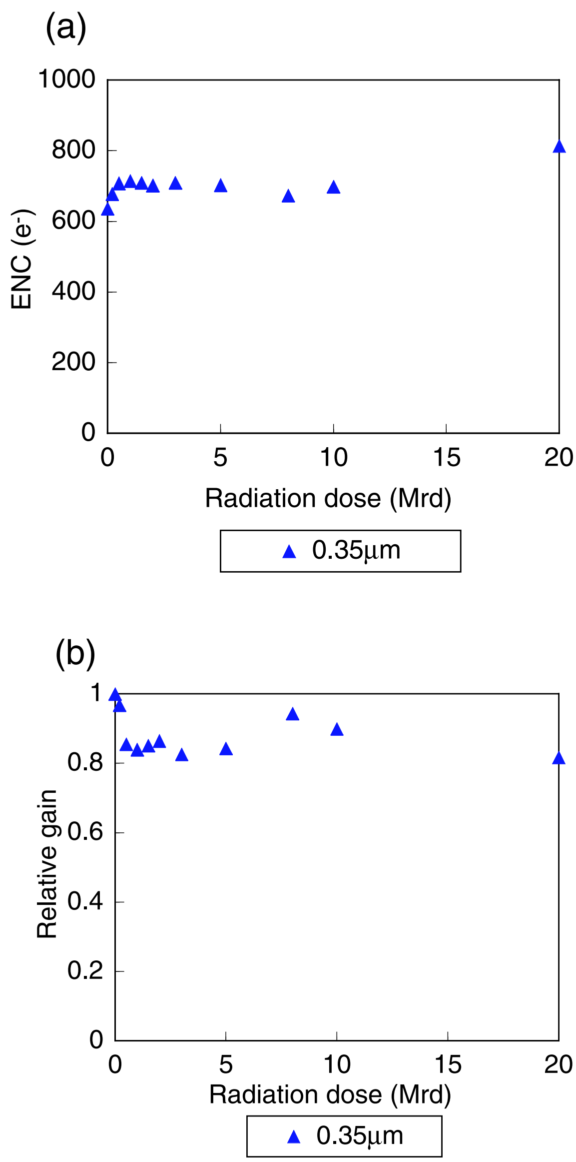

Fig. 2. Measured noise (a) and gain (b) of the VA1 chip fabricated in the 0.35 μm process with 20 pF of load capacitance as a function of the total radiation dose.

IV. Results on VA1 Chips

VA1 samples are irradiated by a ^{60}Co gamma-ray source in the Research Center for Nuclear Science and Technology at the University of Tokyo. The average dose rate is approximately 1 krd/min. In order to simulate a running environment, proper DC bias currents and voltages are supplied to the VA1 chips during the irradiation. The samples are annealed for a few days after each irradiation.

Fig. 1 (a) and (b) show measured noise and gain of the VA1 fabricated in the 0.8 μm process with 20 pF of load capacitance as a function of the total radiation dose. The results obtained from the VA1 fabricated in the 1.2 μm process are also shown in the figures for comparison. The improvement in radiation hardness for the 0.8 μm technology is quite significant. The fractional noise increase of the 0.8 μm VA1 is measured to be 0.13%/krd, which is more than 10 times better than the result from the 1.2 μm VA1. The 0.8 μm VA1 is found to stop functioning between 1 Mrd and 1.2 Mrd.

Fig. 2 (a) and (b) show the measured noise and gain of the VA1 fabricated in the 0.35 μm process with 20 pF of load capacitance as a function of the total radiation dose. Note that the initial noise is larger for the 0.35 μm VA1 than the other VA1s due to the different shaping times. Under the same conditions, the noise performance of the 0.35 μm VA1 is equivalent to the original VA1. After a small degradation of the noise and gain, no further significant degradation is observed. The sample is still functional after 20 Mrd of total radiation dose.

Fig. 3 shows the fractional noise increase as a function of the oxide thickness (t_{ox}). Fig. 4 shows the fractional gain degradation as a function of the oxide thickness. In

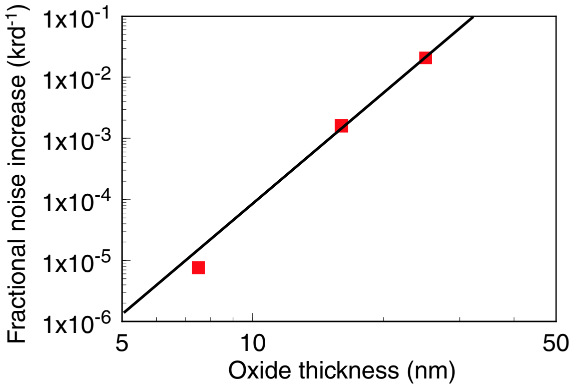

Fig. 3. Fractional noise increase as a function of the oxide thickness (t_{ox}). A line with $y = at_{ox}^6$ is also shown as a reference.

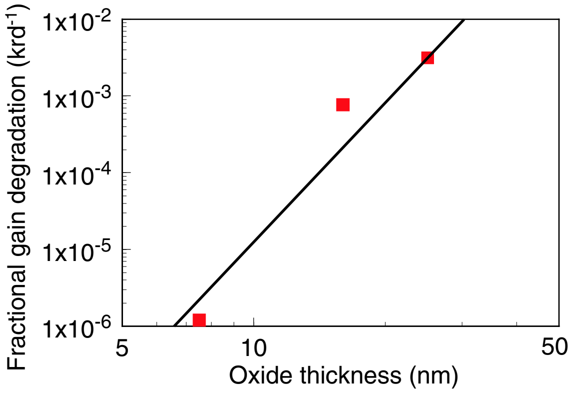

Fig. 4. Fractional gain degradation as a function of the oxide thickness (t_{ox}). A line with $y = at_{ox}^6$ is also shown as a reference.

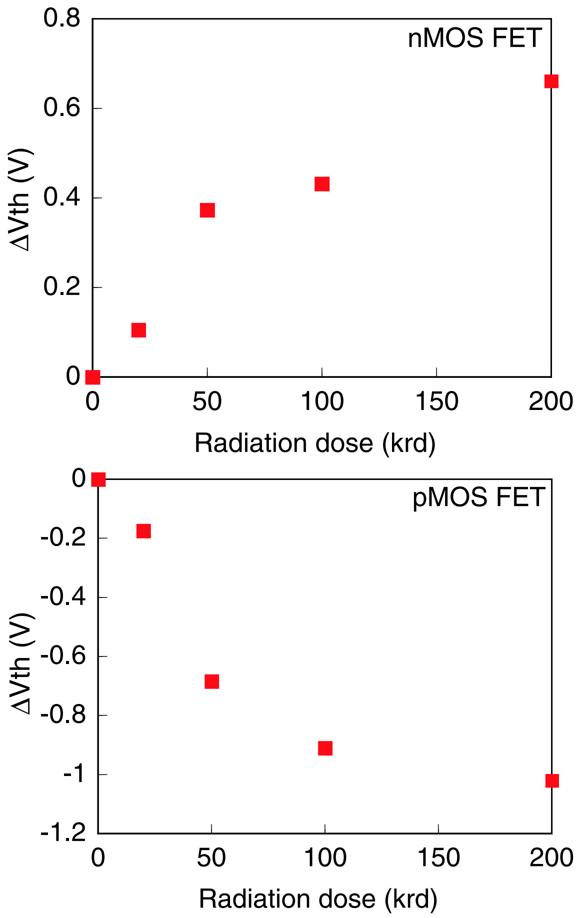

Fig. 5. Threshold voltage shift of MOS FETs as a function of the total radiation dose.

these plots, the fractional noise increase and the fractional gain degradation for the 0.35 μm VA1 are obtained assuming the linear dependence of the noise and the gain on the radiation dose. A line with $y = at_{ox}^6$ is also shown as reference. We find that the radiation hardness scales as t_{ox}^{-6} in the case of the noise and t_{ox}^{-3} in the case of the gain, for oxide thicknesses from 1.2 μm to 0.8 μm. The difference may indicate the difference in the damage mechanism. The change in noise and gain from 0.8 μm to 0.35 μm appears to be larger than a sixth power dependence on the thickness of the oxide. Escape of hole traps by the tunneling effect must be dominant for sub-micron technologies. Furthermore, almost all traps escape by tunneling for the device fabricated in the 0.35 μm process and the total dose effect is negligible.

V. Results on FETs

Radiation effects on MOS FETs fabricated in the AMS 1.2 μm process are measured. W/L of the FETs is 30/1.2 μm for both n-channel and p-channel MOS samples. FET samples are irradiated in a similar manner as the VA1 samples.

Fig. 5 shows the threshold voltage shift of n-channel and p-channel MOS FETs as a function of the total radiation dose. The n-channel MOS FET shows a positive threshold voltage shift, while the p-channel MOS FET shows a negative threshold voltage shift. This indicates that the number of increased interface traps ($\Delta \mathrm{N_{it}}$) is much larger than that of increased oxide trap ($\Delta \mathrm{N_{ot}}$), since oxide traps always produce negative shifts in the threshold voltage while interface traps produce positive threshold shifts for the n-channel MOS FET and negative threshold shifts for the p-channel MOS FET.

We expect that degradation of the transconductance of the p-channel MOS FET is the dominant contribution to the increase of the VA1 noise. $1/f$ noise is known to be negligible in the VA before irradiation. The equivalent noise charge (ENC) of the VA1 can be expressed as a function of the transconductance of the input p-channel MOS FET (g_m) as[4], [5];

$$ENC = \frac{C_t \mathrm{e}}{q}\sqrt{\frac{nkT}{3g_m T_p}} \tag{1}$$

where C_t is total load capacitance, e is the base of natural logarithms, q is the magnitude of the electron charge, n is a slope factor and is about 1.2, k is the Boltzmann constant, T is the absolute temperature, and T_p is the peaking time.

Fig. 6 shows the transconductance of the MOS FET samples as a function of the total radiation dose. (Note that

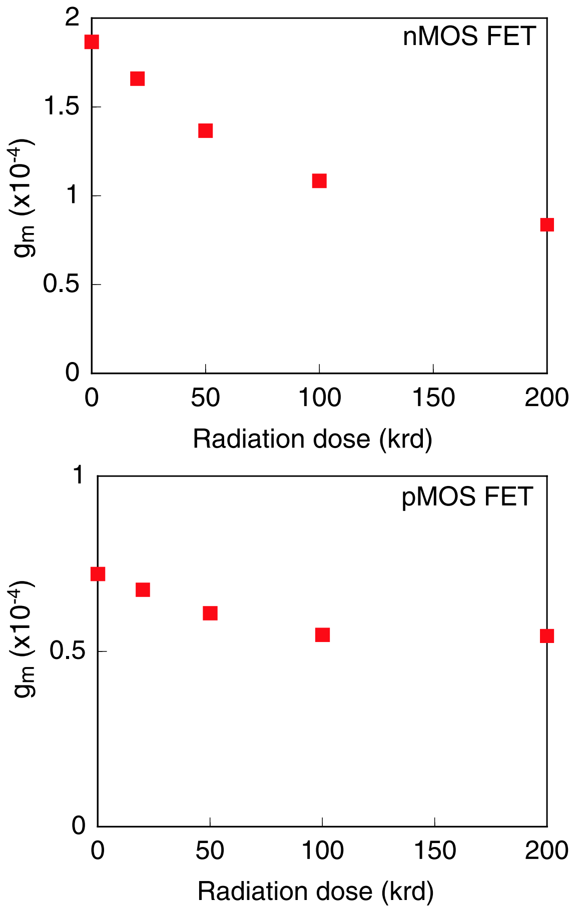

Fig. 6. Transconductance of MOS FETs as a function of the total radiation dose.

the size of the MOS FET tested here is different from the FET used for the VA1 input.) The transconductance of the FET is found to degrade by 24% after 200 krd irradiation, which is expected to increase the noise coefficient for the load capacitance by a factor of 1.15. On the other hand, the noise coefficient for the 1.2 μm VA1 is measured to be 7.2 e$^-$/pF before irradiation and 24.2 e$^-$/pF after 200 krd of irradiation. This indicates that the degradation of the transconductance of the input p-channel MOS FET is not the dominant source of the increase of the VA1 noise after irradiation.

To further understand the source of the increase of the VA1 noise due to radiation, the numbers of increased oxide traps (ΔN_{ot}) and interface traps (ΔN_{it}) are investigated. $1/f$ noise increase is expected to be proportional to the square root of ΔN_{ot} while the transconductance is weakly dependent on ΔN_{it}. Fig. 7 and 8 show ΔN_{ot} and ΔN_{it}, respectively, as a function of the total radiation dose. The value of ΔN_{it} is found to be larger than the ΔN_{ot} by a factor of 2 to 4. This is consistent with the above arguments based on the direction of the threshold voltage shift.

We estimate the $1/f$ noise increase from ΔN_{ot}. We define spectral density of $1/f$ noise as;

$$v_{1/f}^2 = \frac{K_f}{WLC_{ox}^2 f}[\mathrm{V^2/Hz}] \tag{2}$$

where f is the frequency, W(L) is the width(length) of the gate oxide, C_{ox} is the unit capacitance of the gate oxide, and K_f is a noise constant. The increase of K_f (ΔK_f) is proportional to ΔN_{ot}; $\Delta K_f = \alpha \times \Delta N_{ot}$, where α is a process dependent damage constant. ΔK_f can be related to $\Delta ENC = \sqrt{ENC^2 - ENC_0^2}$ of the VA1 using the transfer function of the VA1 as;

$$\Delta K_f = \left(\frac{\Delta ENC}{95C_t}\right)^2 WLC_{ox}^2 \times 10^{-11}\ [\mathrm{V^2pF^2/\mu m^2}]. \tag{3}$$

Assuming that the increased VA1 noise, $\Delta ENC = 1540$ e$^-$ at 200 krd is dominated by the contribution from the $1/f$ noise, we obtain $\alpha = 1.61 \times 10^{-16}$ V^{2}pF^2. This is close

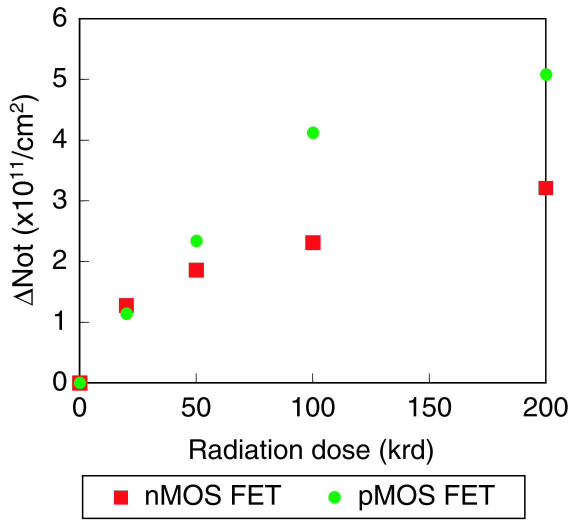

Fig. 7. Number of increased oxide trap (ΔN_{ot}) of MOS FETs as a function of the total radiation dose.

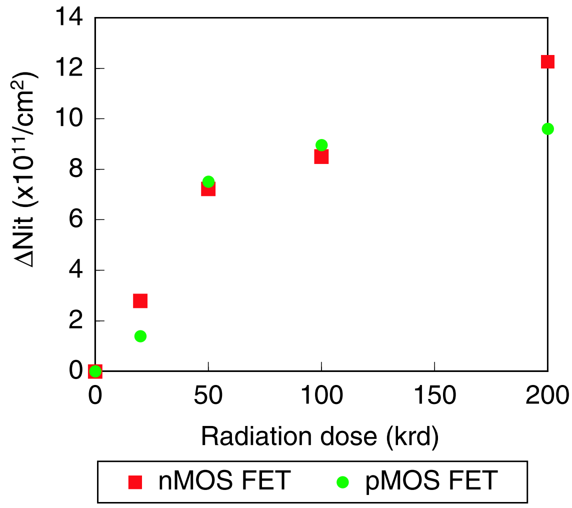

Fig. 8. Number of increased interface trap (ΔN_{it}) of MOS FETs as a function of the total radiation dose.

to the value $\alpha = 0.95 \times 10^{-16}$ V^{2}pF^2 obtained by Matsushita *et al.*[9]. Although the agreement is good enough taking into account the process dependence of α, this value is still too large to be consistent with measured noise at 50 and 100 krd, since ΔENC is proportional to $\sqrt{\Delta K_f}$ (or $\sqrt{\Delta \mathrm{N_{ot}}}$). This indicates that the increase of $1/f$ noise is not the dominant source of the increase of the VA1 noise after irradiation. Further investigation is necessary to understand the mechanism to increase VA1 noise after irradiation. It will also be of great interest to measure the similar parameters of FETs fabricated in the AMS 0.8 μm and 0.35 μm process technologies and to understand the relation with the increased VA1 noise.

VI. Conclusions

We have successfully developed a radiation-hard front-end VLSI using a 0.35 μm process technology. Test samples are found to be functional after total 20 Mrd of gamma-ray irradiation. We find that the radiation hardness improves at t_{ox}^{-6} or better with sub-micron process technologies. Several parameters of MOS FETs are measured as a function of radiation dose to understand the sources of the increase of the VA1 noise. The degradation of transconductance of input FET and the increase of $1/f$ noise are considered as sources of the increase of the VA1 noise after irradiation. Measurement results indicate that neither of them is the dominant source of the increase of the VA1 noise. Further investigation is necessary to understand the mechanism of radiation damage in the VA1.

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